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High Power Evaluation of Thin Metal Foil Lead-Acid Cells

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13. ABSTRACT *(Maximum 200 words)*
Results are presented on prototype 1.2 Ah thin metal foil lead-acid cells manufactured by Bolder Battery, Inc. Cells were evaluated under constant current discharge conditions for pulse power application between 1 to 500 amps at ambient conditions. The volumetric power and energy densities at the 30 second rate for 1.2 Ah cells were found to be 1.35 MW/cubic meter and 192 MJ/cubic meter, respectively. Cycle life of the 1.2 Ah cells was found to be about 250 cycles for 100 percent depth of discharge at rates up to 10 amps. Cells were capable of very fast recharge and were able to be charged in less than 3 minutes to 68 percent of the discharged capacity.

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INTRODUCTION

Pulse power applications such as electric weapons, electric vehicles, and engine starting require batteries having very high power densities (> 1 MW/m^3) and energy densities (>100 MJ/m^3). Conventional cell designs of aqueous lead-acid batteries, using mono-polar cell construction and thick electrode spirally wound construction have not been shown to deliver the required energy and power densities at pulse power conditions (i.e., at the 30 second rate). More volume efficient high power cell designs, such as those used for bi-polar molten salt and lead-acid cells, have met with limited success, due to engineering complications in sealing bi-polar cells and corrosion failures of metallic bi-polar current collectors [1,2]. Thin metal foil, high surface area spirally wound lead-acid cells therefore offer the most practical approach for achieving a near term pulse power battery. The 1.2 Ah thin metal foil lead-acid cell design developed by Bolder Battery, Inc. has been reported to be capable of 8 kW/kg peak power density, and recharge in less than 7 minutes [3]. It is the objective of this study to confirm the high power capabilities of the Bolder 1.2 Ah cell and provide information for possible use of this cell technology for high power and pulse power applications.

EXPERIMENTAL

Single cell evaluation

Prototype 1.2 Ah thin metal foil (TMF) lead-acid cells were obtained, on loan from Bolder Battery, Inc. The cells are constructed as cylindrical cells using thin metal foil, spirally wound electrodes coated with active material and electrically separated by a glass separator wetted with sulfuric acid electrolyte. The cells are sealed, with a vent, in a plastic cell case with positive and negative current buses at opposite ends of the cell. The cell dimensions are 2.265 cm diameter and 7.12 cm length, excluding the current end buses, giving a cell volume of 28.69 cm^3. As received, cell weights ranged from 78.91 g to 81.70 g and were checked periodically for water loss. The as received cell open circuit voltages were between 2.161 V and 2.163 V. Each cell was top charged at 50 mA to a 2.6 V cell cutoff voltage prior to evaluation.

Cells were evaluated at ambient temperature conditions using constant current discharge to 1.5 V cell voltage cutoff. Discharge rates above 250 A utilized a cell voltage cutoff limit of 0.5 V. Electrical end connection to all cells tested was provided by use of 0.25 inch thick copper busing at the positive and negative terminals to reduce IR losses. Electrical contact of the busing to the cells was accomplished by applying spring-loaded force onto the cell end terminals through the use of a C-clamp holder. Insulation of the electrical connections in the holder was provided by use of 0.5 inch thick boron nitride plate. Stranded 4/0 AWG battery cable was used to make electrical connections between the copper end buses on the cells and the power supply for currents up to 120 A. Discharge currents up to 120 A were applied manually using a Dynaload model DLVP 50-120-1500 power supply on single cells in series with three series connected 25 Ah Gates Cyclon BC cells to provide sufficient driving voltage. Higher current discharges above 120 A were performed using a Battamatic water-cooled automatic battery tester and 2/0 AWG battery cable, with single cells in series with a 24 V nickel cadmium aircraft battery to provide sufficient driving voltage at the higher rates. Cell voltages were measured off the copper busing attached to the cells using a Hewlett Packard model 3456A digital voltmeter and recorded on a Nicolet model 320 oscilloscope. Cells were cycled at constant current using a Hewlett Packard 87XM computer controller and Kepco power supply model BOP 20-20M. Unless otherwise noted, all cells were charged at constant current by two step charging at 1 A and 0.1 A to 2.6 V, respectively. Cell skin temperature was monitored using a K-type thermocouple and a Fluke 2176A digital thermometer.

Three cell battery evaluation

A three cell battery was evaluated using three 1.2 Ah Bolder TMF cells in series with 5 mil silver disks between cells to improve the surface electrical contact. The cells were housed in a 1 inch inside diameter stainless steel tube which was insulated from the cells by a wrap of 10 mil Teflon sheet. Electrical connections and testing over the first ten cycles of the battery were performed using the methods described above for the single cell testing up to 120 A between a battery voltage limit of 7.8 V and 4.5 V. The three cell battery was cycled using a Techware Automated Battery Cycler at constant current. The discharge rate was 5 A to a battery cutoff voltage of 4.5 V. Charging was performed as a five step charge at 5 A, 1A, 0.2 A, 0.1 A, and 0.05 A to a cutoff voltage of 7.8 V, respectively, with a five hour charge limit on the fifth step.

RESULTS AND DISCUSSION

Table 1 gives the single cell results for the Bolder 1.2 Ah TMF cell discharged at ambient conditions. Cell polarization at various current discharges is depicted in Figures 1 through 3. The cells were capable of very high current discharge due to their low impedance, thin metal foil electrode design. The typical cell impedance of charged cells was measured to be 1.8 milliohms. Skin temperature measurements performed on cells during cycling showed increases of about 3 to 8 degrees C to occur for discharge rates from 10 to 500 A, respectively. The temperature measurements were obtained in a forced air environment and therefore higher temperatures would be expected under static conditions. The recommended operational temperature range is between -40 and 65 degrees C. The high discharge current capabilities of the 1.2 Ah Bolder TMF cell are given in Figure 4. The average cell voltage decreased slowly to 100 A before falling off at higher rates. Discharge currents above 500 A were not obtained due to limitations of the test equipment and to the load limit of the spring-loaded electrical connection to the cell. However, even with these limitations, the 1.2 Ah Bolder TMF cell was demonstrated to operate at very high power and energy densities as shown in Figures 5 and 6. The volumetric and gravimetric energy/power curves are based on the total weight of the cell (80 g) and the external cell volume (28.69 cm^3). For pulse power conditions, typical volumetric power and energy densities range from 12 kJ/l at 8 kW/l to 70 kJ/l at 2.3 kW/l. The 1.2 Ah Bolder TMF cell was shown to be capable of meeting these requirements, however, larger capacity cells would need to be developed for practical pulse power battery configurations. A comparison of developed lead acid technologies is given in Table 3 for the 30 second discharge rate. As presented, for high power applications the Bolder TMF technology is superior to either the standard mono-polar plate lead-acid or the Gates spirally wound lead-acid batteries. At similar power levels (about 1 MW/m^3), the 1.2 Ah Bolder TMF cell was able to provide six times the energy per given volume of battery and nearly four times the energy for a given weight over the other lead-acid designs. Typical cycle life characteristics of the 1.2 Ah Bolder TMF cell for 100% depth of discharge at 10 A are given in Figure 7. The voltage profile for a typical cycle is given in Figure 8 for the fifteenth cycle. The cell delivered about 250 cycles to 25% of the rated capacity. Limited capacity discharge cycling at 5 A to a 0.25 Ah (20.8% depth of discharge) cutoff delivered improved cycle life to over 400 cycles. Bolder reported 5,000 cycles for cells discharged at 15 A to 13% depth of discharge.

Due to the low impedance cell design of the 1.2 Ah Bolder TMF cell, higher charging rates were examined. Constant current cycling was performed at 50 A discharge to 1.5 V followed by constant current single-step charging at 5 A or 10 A to 2.6 V. The discharge capacity at 50 A was 0.6 Ah and charging at 5 A recharged 75% of the discharged capacity in less than 6 minutes. Recharging at 10 A, following a 50 A, 0.6 Ah discharge, recovered 68% of the discharged capacity in less than 3 minutes. Although fast

recharge of up to 75% of the discharged capacity was possible in under 5 minutes, to achieve full recharge a second lower rate or tapered charging step should be applied.

A three cell battery consisting of three 1.2 Ah Bolder TMF cells in series was similarly discharged to the single cells up to 120 A. Table 2 shows the results for the three cell battery results at ambient conditions. The results are similar to those for the single cell and show balanced cell behavior. Figures 9 through 11 give the polarization curves for the high current discharges of the three cell 1.2 Ah Bolder battery at ambient conditions. After obtaining the polarization data, the three cell battery was placed on 5 mA trickle charge for four months to simulate a storage scenario. After four months of trickle charge, the three cell battery was disassembled to observe and measure the individual cell characteristics. The average weight loss of each cell was found to be only 0.3%. The cell open circuit voltages were measured to be 2.1735 V, 2.1709 V, and 2.1737 V, respectively. Observation of the cells showed that the negative current bus of the middle cell (lowest cell voltage) was depressed into the plastic cell case. The plastic cell case immediately surrounding the bus appeared to have melted, probably due to IR heating from the earlier high current discharges. The buses of all of the cells were cleaned and reassembled in series as previously described and cycled as a three cell 1.2 Ah battery. Figure 12 depicts the cycle behavior of the three cell 1.2 Ah Bolder battery after four month trickle charge at 5 mA. Initially, the observed battery capacity was about 10% less than the results obtained before storage. However, the battery capacity faded rapidly after only 40 cycles. It is believed this is due to the bus failure described above which may have affected the spiral winding in the damaged cell. Since the cells were on loan from Bolder, future postmortem by Bolder is needed to verify the failure mode.

CONCLUSIONS

Results obtained for the high rate evaluation of the 1.2 Ah Bolder TMF cells confirmed the high power capabilities reported by Bolder Battery, Inc. [3]. Energy densities at high power levels (i.e., 30 second rate) for the 1.2 Ah Bolder TMF cell were found to be superior over standard mono-polar plate and spirally wound lead-acid technologies. Useful cycle life was found to be limited to about 250 cycles for deep discharge at discharge rates up to 10 A, which compared well to the 300 cycles reported by Bolder [4]. Limited capacity discharge cycling at 5 A to 20% depth of discharge, (0.25 Ah) resulted in improved cycle life to over 400 cycles. Very fast recharge of up to 75% of the capacity delivered for a 50 A discharge was obtained in less than 3 minutes and was possible due to the low impedance design of the cell. The three cell 1.2 Ah Bolder battery cycling results were observed to be lower than the single cell results. This was believed to be due to a bus cell failure observed on the negative bus of the middle series cell. Excessive IR heating during the higher rate discharge cycles before trickle charge storage is believed to have caused the plastic cell case to melt allowing the bus to be depressed into the cell. The three cell battery was assembled in a Teflon insulated metal tube which may not have allowed sufficient heat conduction to cool the cells during the high current testing. Future battery configurations for high power will need to account for this heating effect to avoid similar failures.

ACKNOWLEDGMENTS

The authors are grateful to Bolder Battery, Inc. for loaning the cells used in this study. Additional acknowledgements are given to Martin Sulkes for providing use of the high current power supply for the 250 A and 500 A discharge cycles, Dr. Mark Salomon for digitizing the three cell battery data, and Dr. W. K. Behl for valuable technical discussions.

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4. M. A. Ruderman, Bolder Battery Incorporated, Private communication.

Table 1. Discharge performance of 1.2 Ah Bolder TMF cell.

2.6 V to 1.5 V

DISCHARGE CURRENT	DISCHARGE TIME	AVERAGE CELL VOLTAGE	CELL CAPACITY	PERCENT OF RATED CAPACITY
Amps	SEC	V	Ah	%
5	704	1.98	0.98	82
10	321	1.97	0.89	74
20	142	1.93	0.79	66
50	45	1.82	0.63	53
100	18	1.69	0.50	42
250 *	5.7	1.32	0.40	33
500 *	1.4	0.71	0.19	16

* Discharged to 0.5 V.

Table 2. Discharge performance of three cell 1.2 Ah Bolder battery.

7.8 V to 4.5 V

DISCHARGE CURRENT	DISCHARGE TIME	AVERAGE BATTERY VOLTAGE	BATTERY CAPACITY	PERCENT OF RATED CAPACITY
Amps	SEC	V	Ah	%
1	4,464	5.90	1.24	103
5	777	5.54	1.08	90
10	340	5.45	0.94	79
20	136	5.13	0.76	63
50	41	4.92	0.57	47
100	18	4.77	0.50	42
120	14	4.78	0.47	39

Table 3. Performance of developed lead-acid technologies.

CELL / BATTERY	PERFORMANCE AT 30 SEC DISCHARGE RATE
SLI, 100 Ah 12 V Battery	29 MJ/cubic meter @ 0.95 MW/cubic meter 17 kJ/kg @ 0.56 kW/kg
Gates, 25 Ah Spiral Wound Cell	32 MJ/cubic meter @ 1.1 MW/cubic meter 11 kJ/kg @ 0.38 kW/kg
Bolder, 1.2 Ah Thin Metal Foil Cell	192 MJ/cubic meter @ 1.35 MW/cubic meter 67 kJ/kg @ 0.47 kW/kg

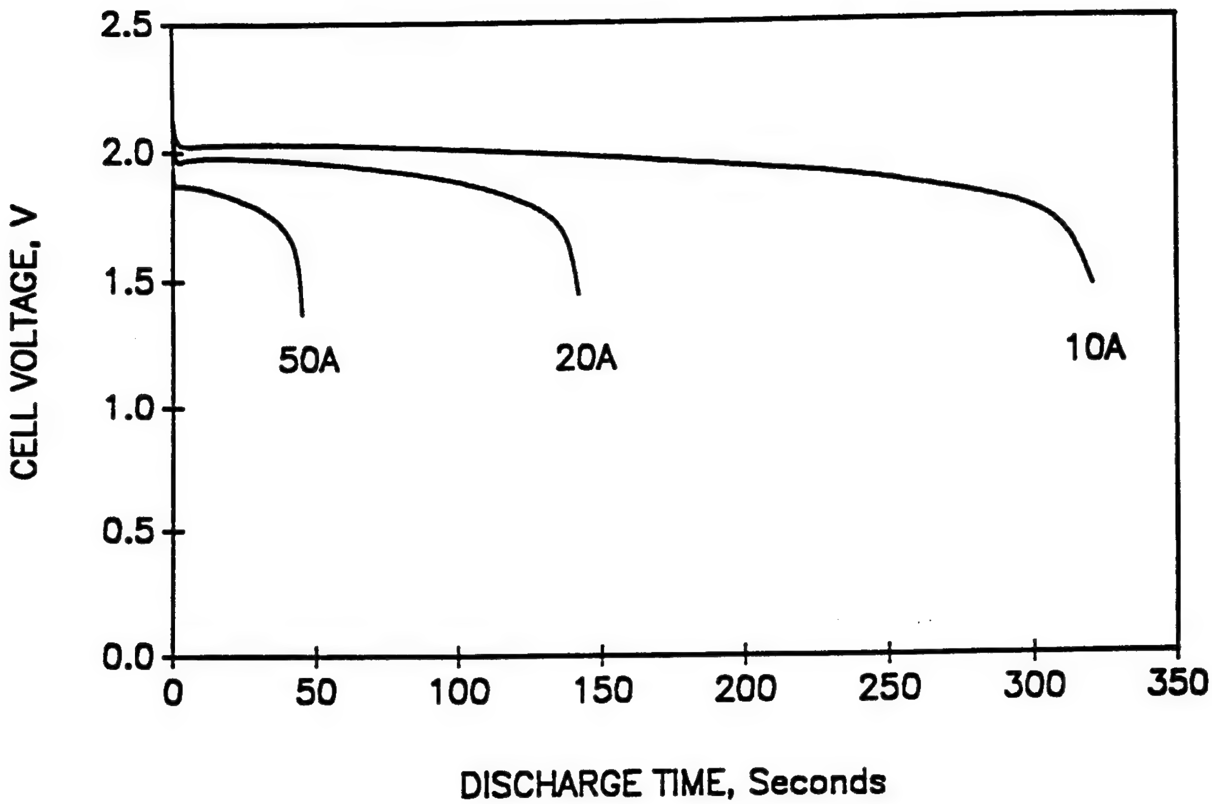

Figure 1. Polarization curves for 1.2 Ah Bolder TMF cell at 10 A, 20 A, and 50 A.

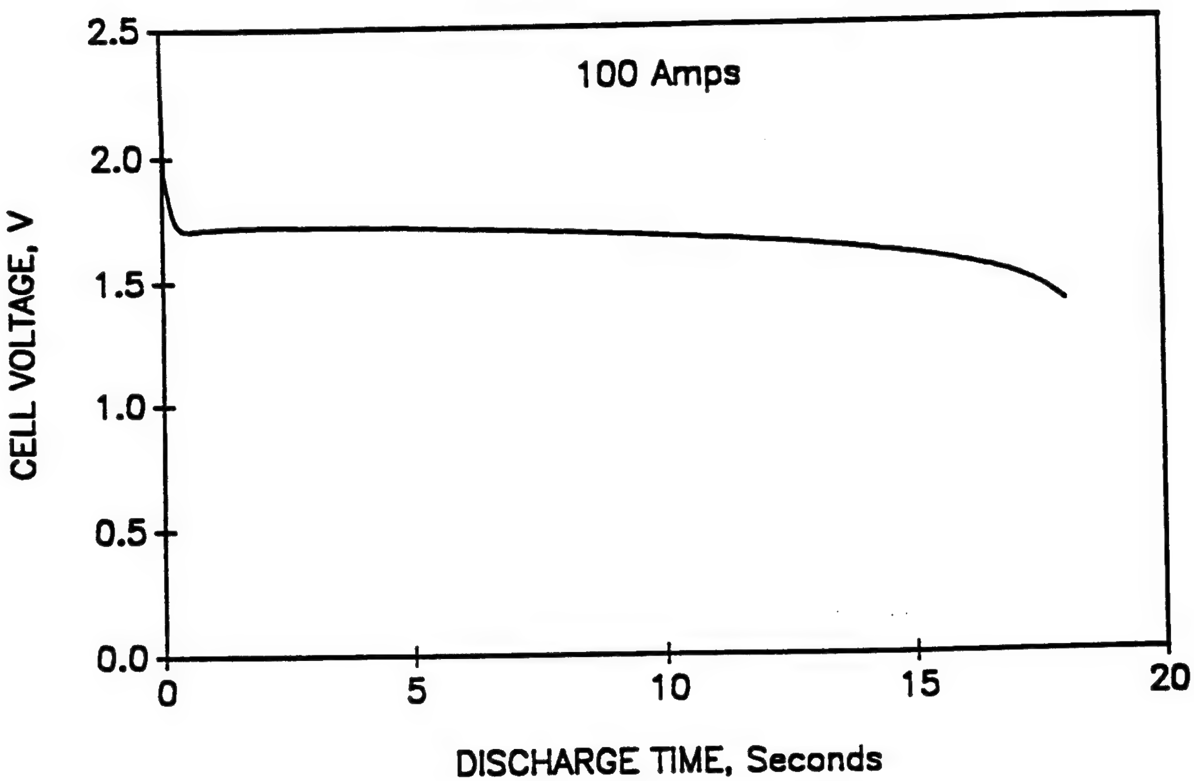

Figure 2. Polarization curve for 1.2 Ah Bolder TMF cell at 100 A.

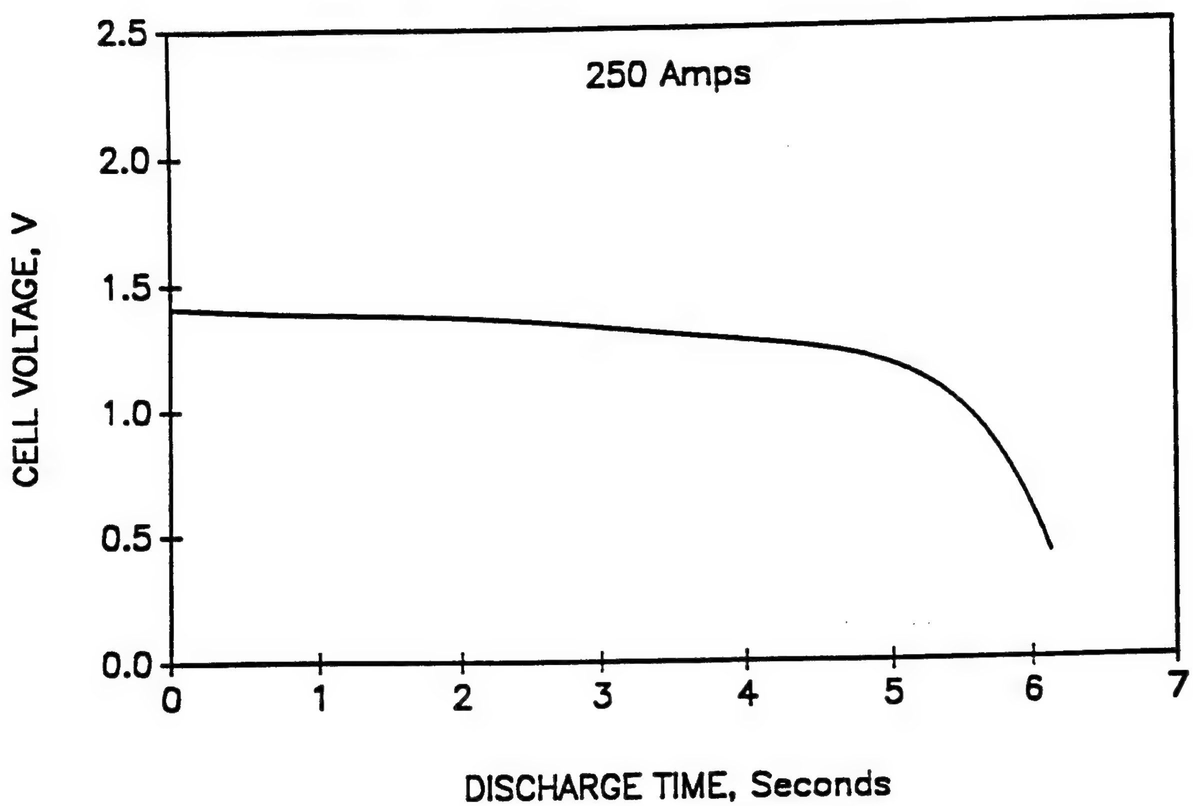

Figure 3. Polarization curve for 1.2 Ah Bolder TMF cell at 250 A.

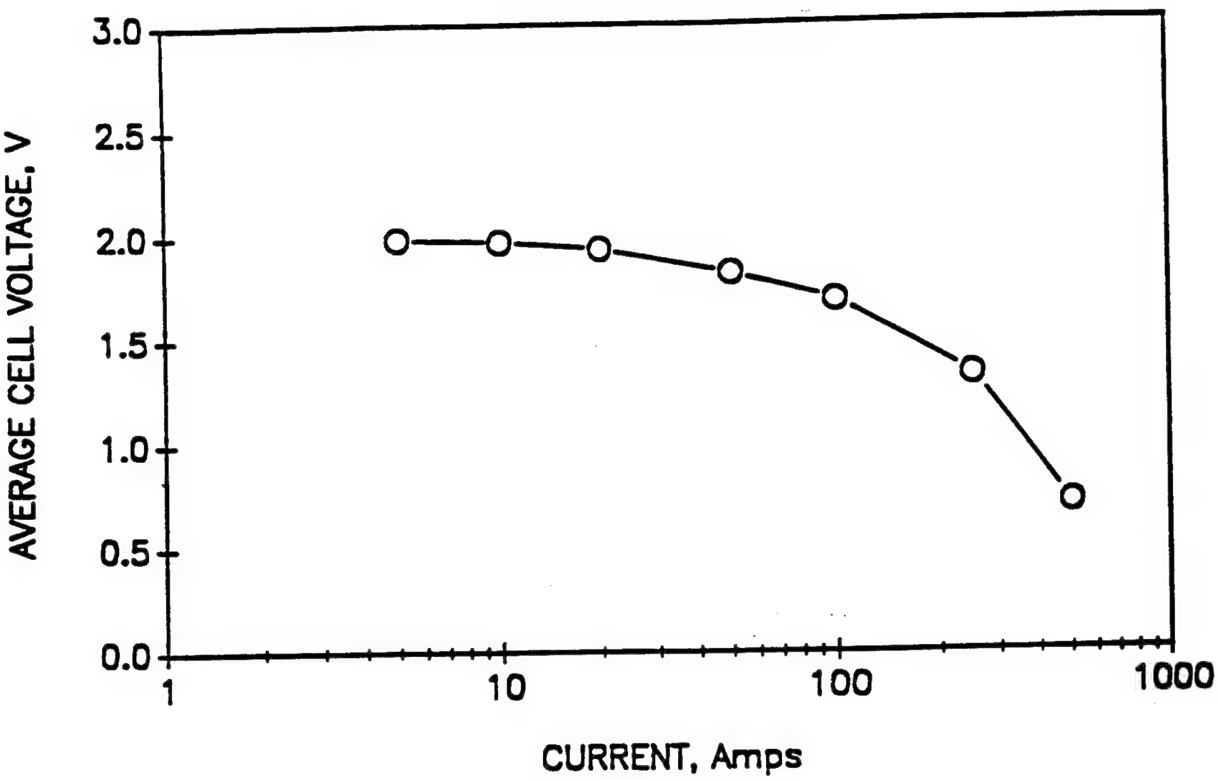

Figure 4. Average cell voltage as a function of current for 1.2 Ah Bolder TMF cell.

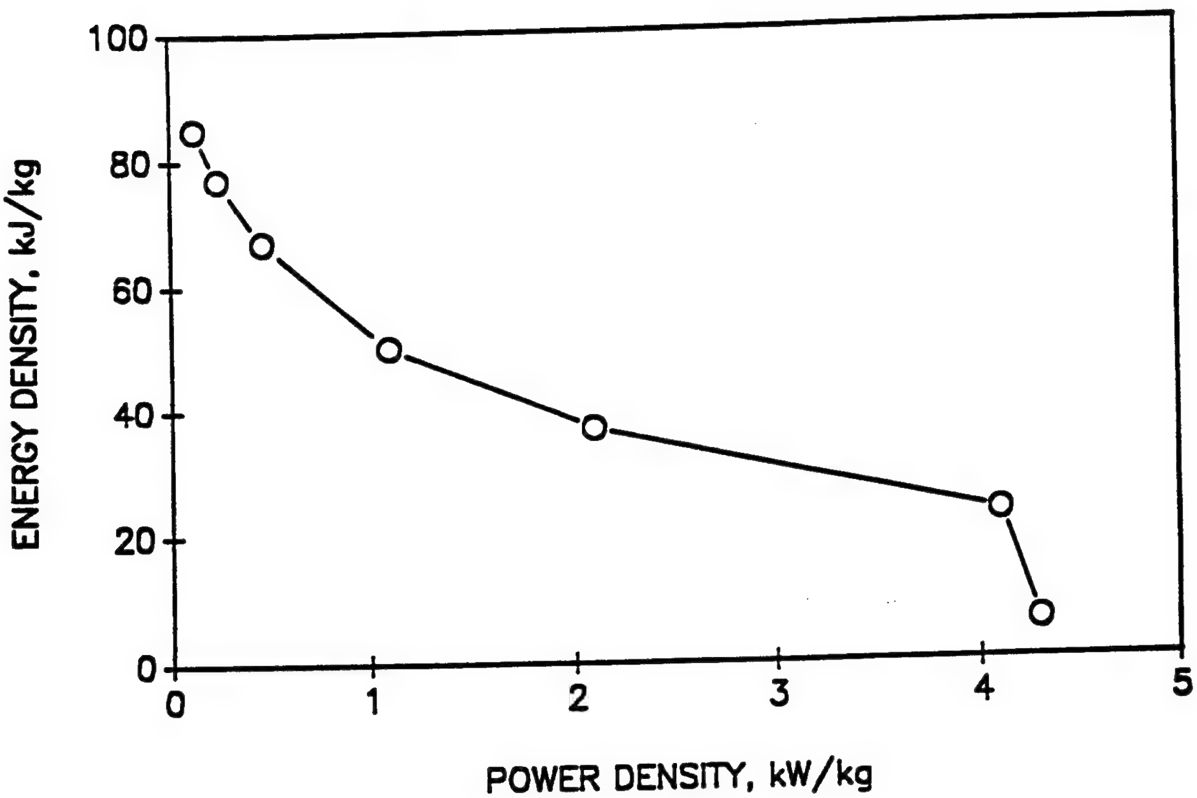

Figure 5. Gravimetric energy/power densities for 1.2 Ah Bolder TMF cell.

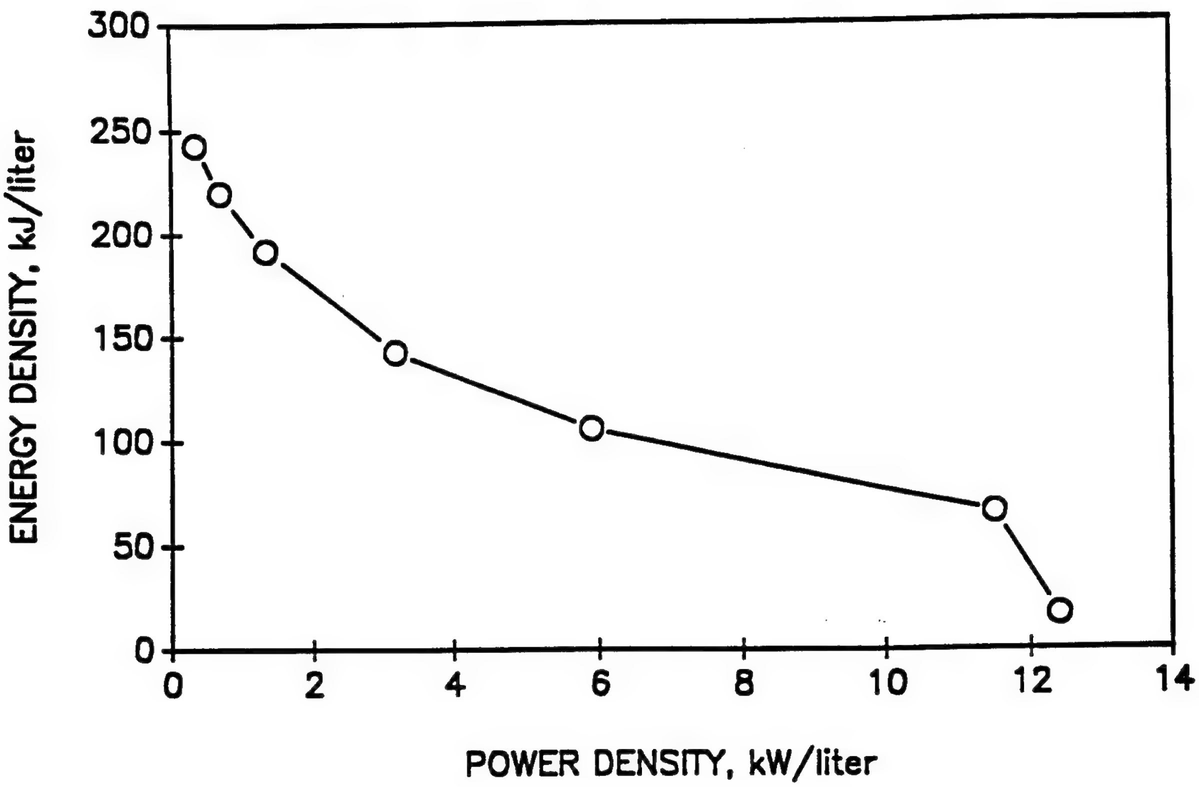

Figure 6. Volumetric energy/power densities for 1.2 Ah Bolder TMF cell.

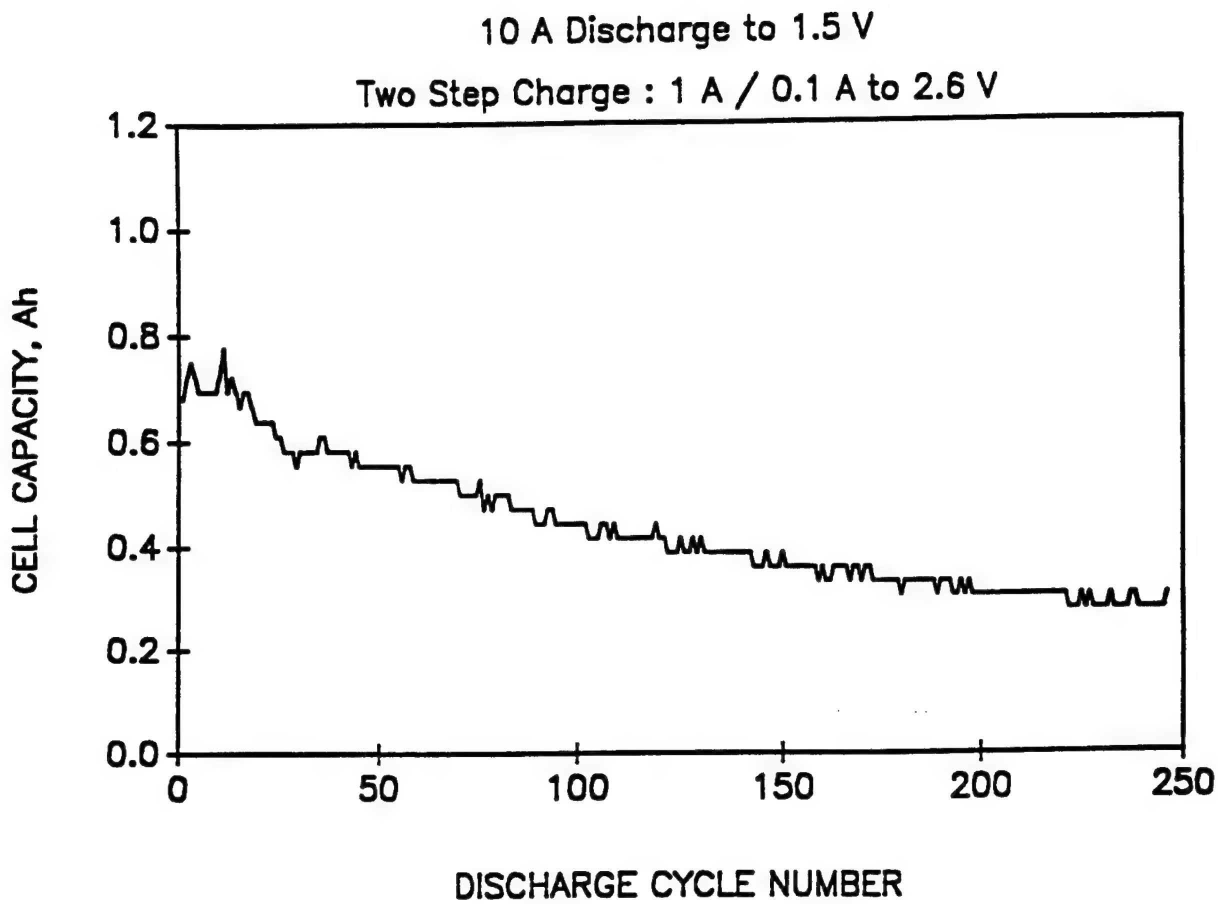

Figure 7. Cycle life performance of 1.2 Ah Bolder TMF cell.

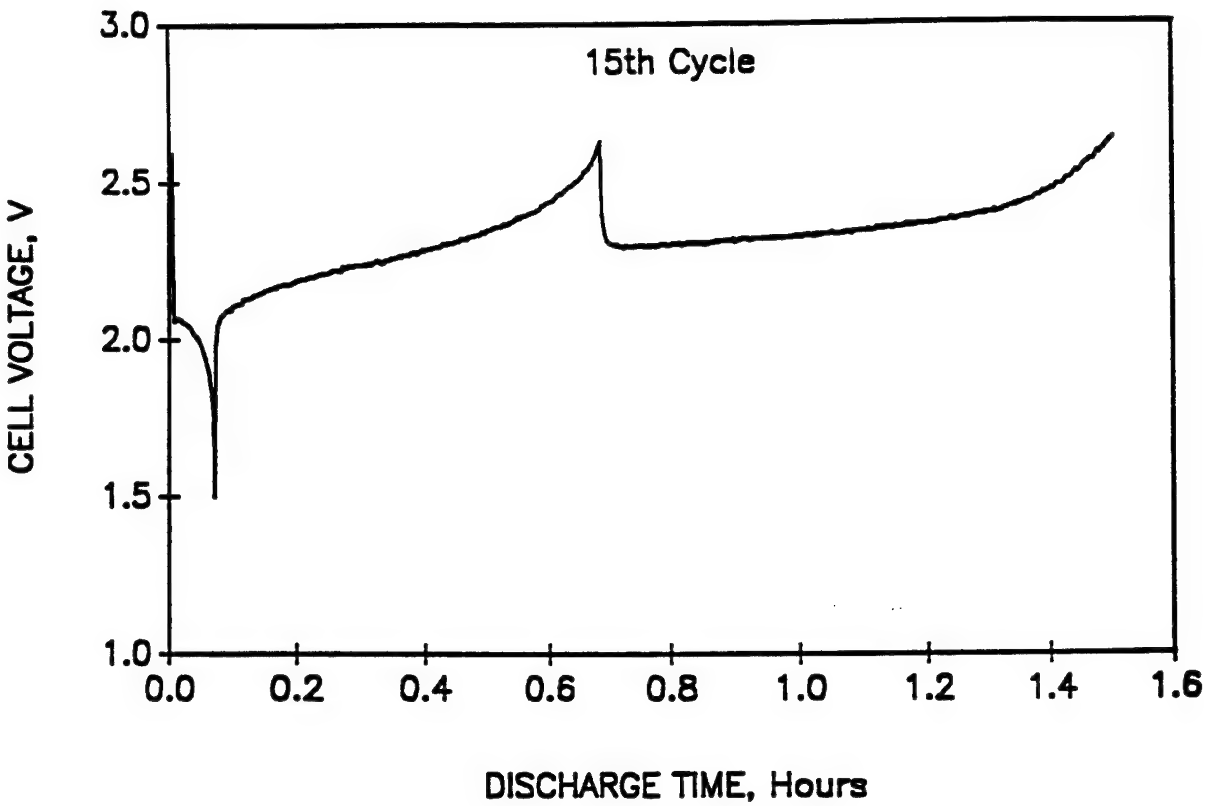

Figure 8. Typical cycle of 1.2 Ah Bolder TMF cell. Discharged at 10 A with two step charge at 1 A and 0.1 A, respectively.

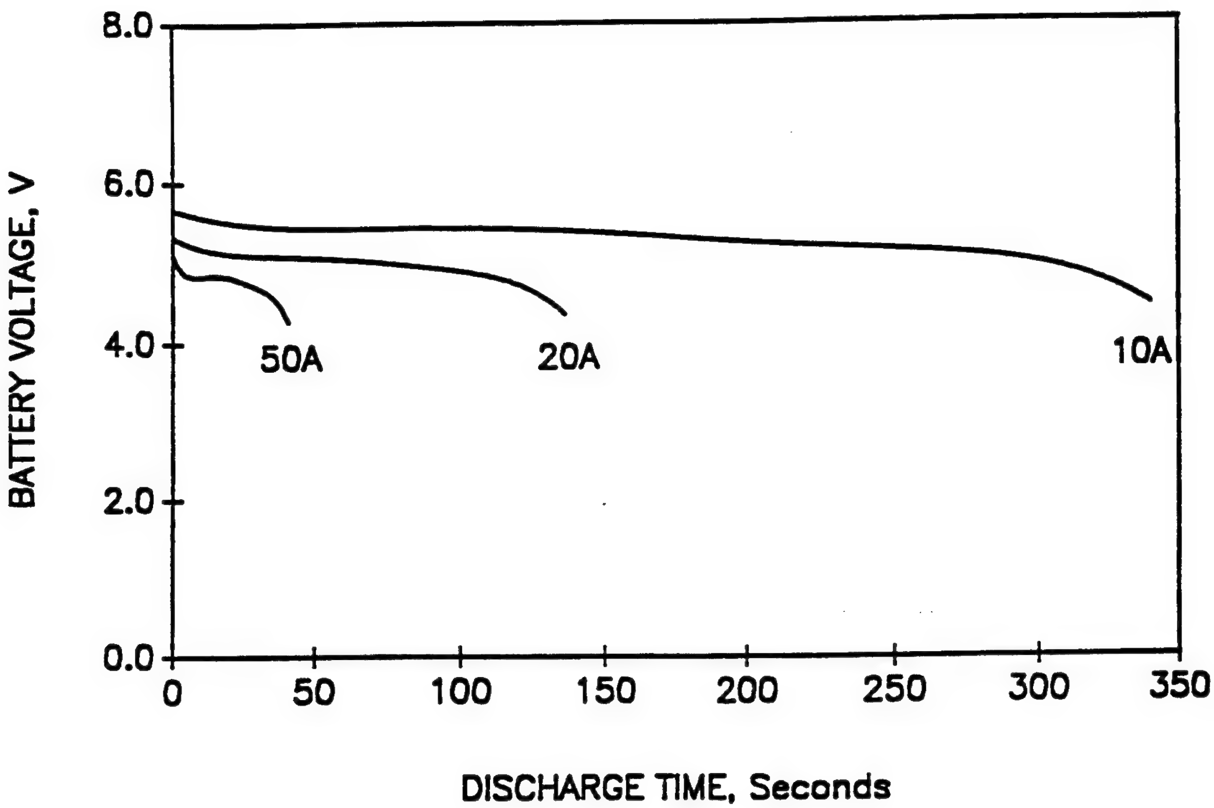

Figure 9. Polarization curve for three cell 1.2 Ah Bolder battery.

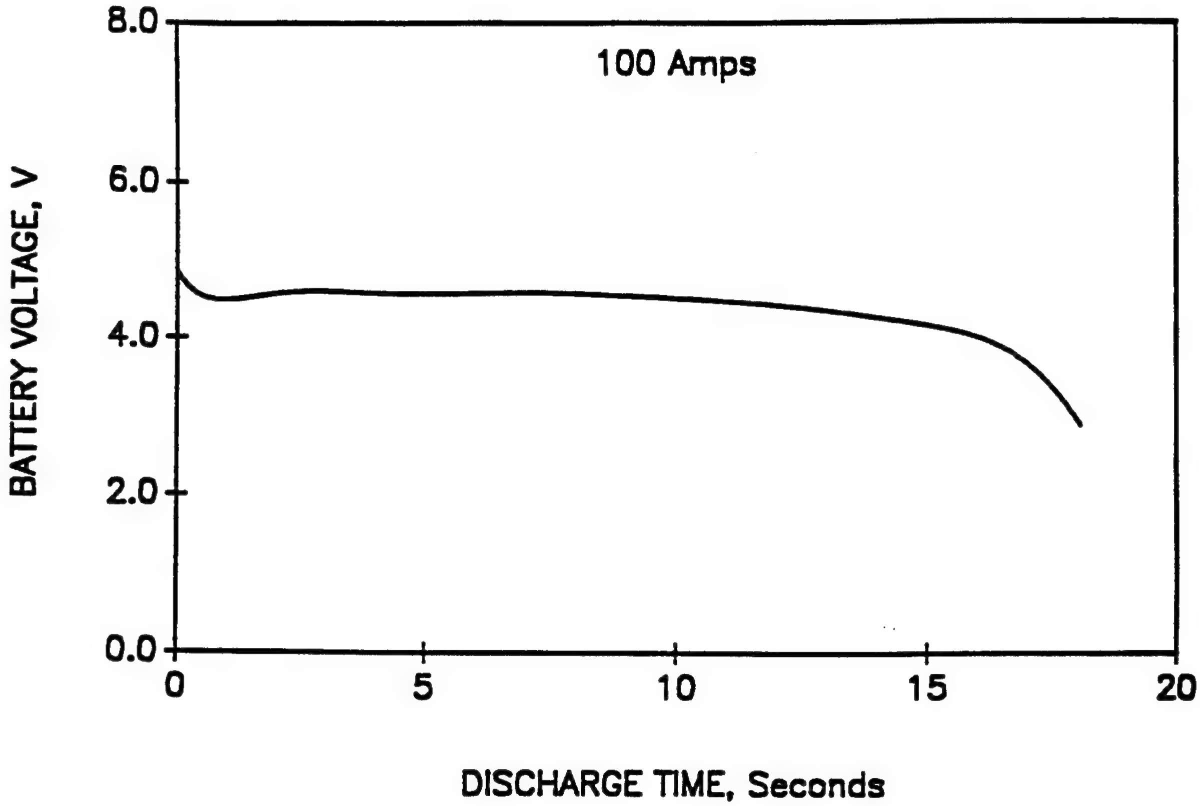

Figure 10. Polarization curve for three cell 1.2 Ah Bolder battery at 100 A.

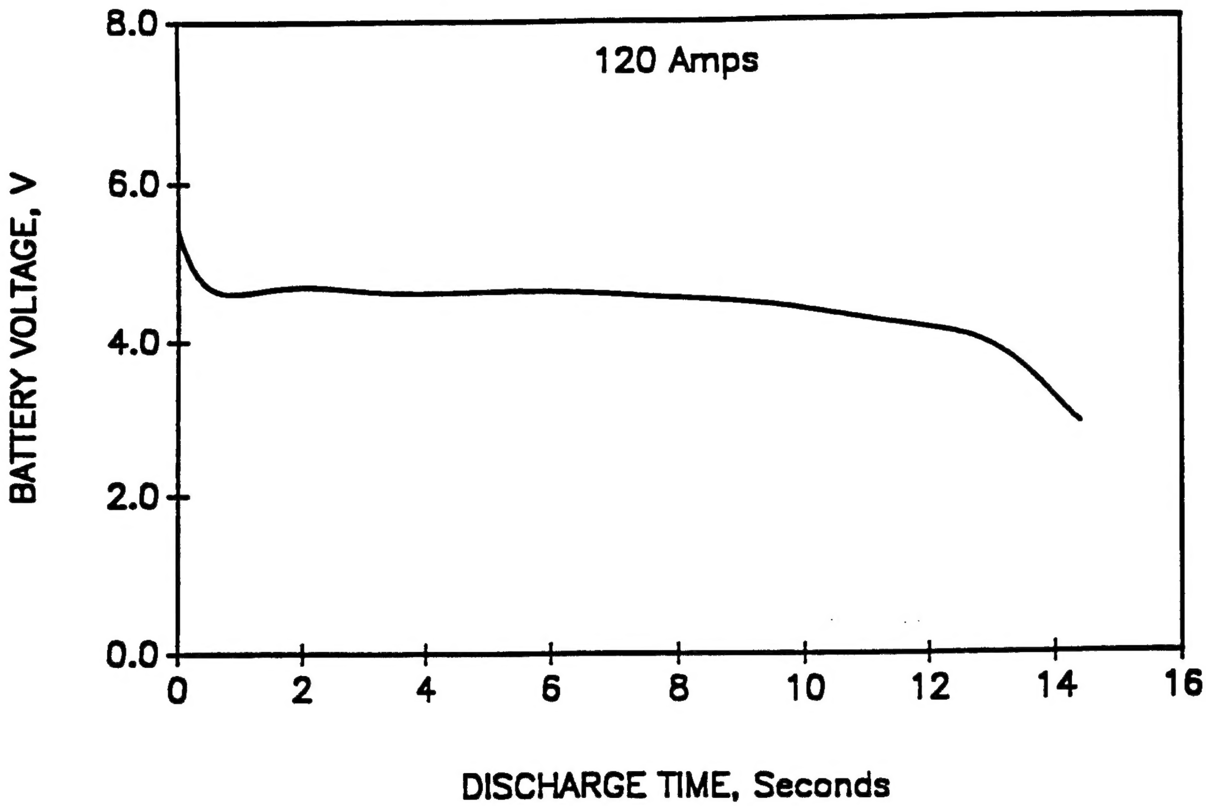

Figure 11. Polarization curve for three cell 1.2 Ah Bolder battery at 120 A.

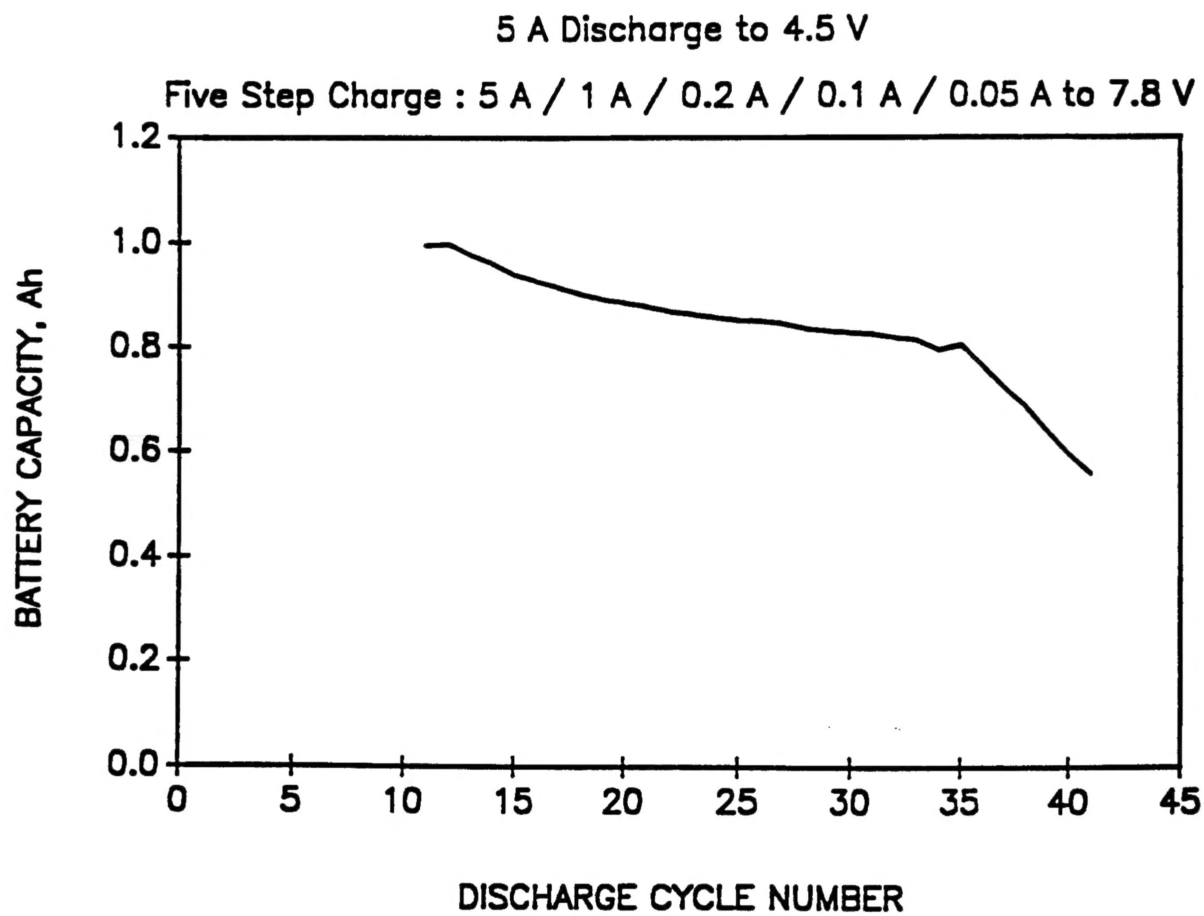

Figure 12. Cycle life performance of three cell 1.2 Ah Bolder battery after four month trickle charge at 5 mA.

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